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Mangrove forest: An important coastal ecosystem to intercept river microplastics

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ABSTRACT

The research on transportation of river microplastics (MPs) mainly focuses on the estimations of the total contents of river MPs entering the ocean, while the related transportation processes and influence factors were still largely unknown. In our study, the role of mangrove forest, a special tropical ecosystem in the estuary, on the transportations of MPs from rivers to ocean was explored. Except for the ND river with the absence of mangrove forest, the MPs collected from the water sample of the river upstream were much higher than their corresponding downstream ($p < 0.05$), with the interception rate of riverine MPs by mangrove forests ranging from 12.86% to 56% in dry season and 10.57%–42% in rainy season. The MPs with the characteristics of high density, larger size and regular shape were more easily intercepted. Furthermore, the combined effects of ecological indicators, the properties of mangrove and the hydrodynamic factors jointly determined the interception rates of MPs. This study provides a new perspective and data support for quantifying mangrove forests intercepting MPs in rivers as a factor of MPs retention in global rivers.

1. Introduction

The annual output of global plastic products had raised significantly from 1.5 million tons in the 1950s to 348 million tons in 2017 due to their lightweight, versatility, strength and durability (Mai et al., 2019; Plastics Europe, 2018; Wright et al., 2013). Plastic particles with size less than 5 mm, known as microplastics (MPs), in particular, have caused serious environmental and ecological problems, including release of internal toxic substances into the water (Chen et al., 2019; Seidensticker et al., 2017), absorption of organic/inorganic contaminants to enhance their availability to biota, etc. (Alimi et al., 2018; Barboza et al., 2020; Wagner et al., 2019). Environmental pollution from MPs is a matter of growing concern because of human health implications (Bagheri et al., 2021; Bhat et al., 2021; Rasheed et al., 2020a; Rashid et al., 2021). Early research on the spatial and temporal distributions of MPs in environmental matrix (soil/sediment, water, etc.) were mainly concentrated on the marine environment, including the Pacific Ocean (Mu et al., 2019), the Arctic Ocean (Bergmann et al., 2017), the Indian Ocean and even deep-sea sediments in the Atlantic (Imhof et al., 2017; Van Cauwenberghe et al., 2013).

With further research on marine MPs, it is estimated that there are more than 150 million tons of plastic debris in the global oceans (Zhao et al., 2019), and 90% of the debris have terrestrial origins (Boucher and Friot, 2017). Rivers are considered to an important carrier to transport various kinds of plastic debris from land to the sea (Baldwin et al., 2016; Sher et al., 2021). Therefore, a better understanding of the quantity of MPs input from rivers to the ocean helps to refine our understanding of marine MPs pollution sources and pathways, while enabling a more accurate estimation of the quantity of marine MPs.

From the composition and quantity of point-source MPs fluxes explained by modeling (Siegfried et al., 2017), to a global model based on waste management, population density and hydrological information (Lebreton et al., 2017), to a model using mismanaged plastic waste (MMPW) as the predictor (Schmidt et al., 2018), to the Global Riverine Export of Microplastics into Seas (GREMiS) model (Van Wijnen et al., 2019), more and more studies developed various models that attempted

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to estimate the contribution of land-based sources (particularly rivers) MPs to the sea. These models allow us to understand the magnitude of MPs imported from land sources into the sea. For example, the model set up by Lebreton et al. (2017) estimated that each year about 1–2.5 million tons of plastic litter flows into the sea in the world, while Asia contributes the most. However, Mai et al. (2019) investigated eight rivers in the Pearl River Delta and calculated that the annual input was 2400–3800 tons of plastic debris, which was much lower than the output value (91000-170000 tons) of MPs distributed in this area by the model. The difference between the final results estimated by the model and the actual result may be partly due to the fact that many influencing factors are not taken into account in the model, such as the most important factor of intercepting MPs on the migration path.

Mangrove forests, as one of the most common ecosystems at the intersection of land and sea, were significantly different from other coastal ecosystems with respect to the transformation of pollutants because of their high productivity and biomass (Bayen et al., 2019; Li et al., 2019). However, nearly all the related studies still focused on investigation of the distribution of MPs in mangrove forest from 520 to 2310 items/kg in Maowei Sea, from 15 to 6168 items/kg in Qinzhou Bay and from 12 to 62.7 items/kg in Singapore with abundance higher than that in surrounding areas (Li et al., 2018; Mohamed Nor and Obbard, 2014).

To adapt to breathing in the soil adjacent to the water and better resist the wind and waves, part of the mangrove roots is transformed into pneumatophores and prop roots. The pneumatophores and prop roots of mangrove plants crisscross in the water to form an effective filter, which can effectively reduce wave energy and turbulence (Barbier et al., 2011; Horstman et al., 2014) and thus has the ability to intercept low density substances from river to sea. For example, Martin et al. recorded that the abundances of marine plastic range from 0.66 ± 0.18 items/m^2 to 1.21 ± 0.53 items/m^2 in the mangrove forests of the Red Sea and Arabian Gulf and believed that where there are mangroves, plastic is trapped before reaching the sea (Martin et al., 2019). Moreover, the inorganic/organic contaminants, including the polycyclic aromatic hydrocarbons and heavy metals, in river were found to be more easily accumulated in mangrove sediments (Bergamaschi et al., 2012; Tam et al., 2001). Therefore, we assumed that the mangrove forest has the potential ability to intercept the MPs reaching from the river to sea. However, till now, there exists no systematics reports investigating the related processes and mechanisms.

The Beibu Gulf is located in the northwest of the South China Sea, from Leizhou Peninsula, Qiongzhou Strait, Hainan Island to Vietnam, and north to Guangxi coast (Xue et al., 2020; Zhang et al., 2018), with the largest area, the most abundant species of mangroves and a large number of rivers flowing into the sea in China (Gong et al., 2019; He et al., 2007), and thus selected as the study area. The first objective of this study was therefore to validate whether the mangrove forests have ability to intercept MPs input from upstream rivers. If so, we will try to evaluate the interception ability, further explore the mechanisms of the interceptions of MPs by mangroves forest, and more specifically explore the relationship between interception rate of mangrove and river flood season, different characteristics of MPs (size, type, etc.), ecological indicators of mangroves, sediment properties and hydrodynamic factors.

2. Materials and methods

2.1. Study area

Five major rivers in the Beibu Gulf were selected for the study, including the Bei Lun river (BL), Mao Ling river (ML), Qin Jiang river (QJ), Jiu Zhou river (JZ) and Nan Du rivers (ND). Other detailed information about the locations of the sampling sites is presented in Fig. 1. No mangrove forest was found at the upstream, downstream and estuary of ND river, which was selected as a control group.

2.2. Examination of MPs in water and sediment samples collected from the rivers

2.2.1. Sample collection

As shown in Fig. 1, for both the river with the presence and absence of mangrove forest, five sampling points were set up as S1, S2, S3, S4, and S5 from the river upstream, mangrove forest (or corresponding locations for ND rivers) to the river downstream. S1 and S5 represent the upstream and downstream zones of the river relative to the mangroves, respectively, while S2, S3, and S4 represent the front, middle, and terminal zones of the mangroves along the river. The water and sediment samples were separately collected using stainless-steel hydrophore and Van Veen Grab Sampler (area = 0.1 m^2, height = 20 cm). All the samples were stored in the clean stainless -steel shovel and immediately transported to the laboratory at 277.15 K until processing.

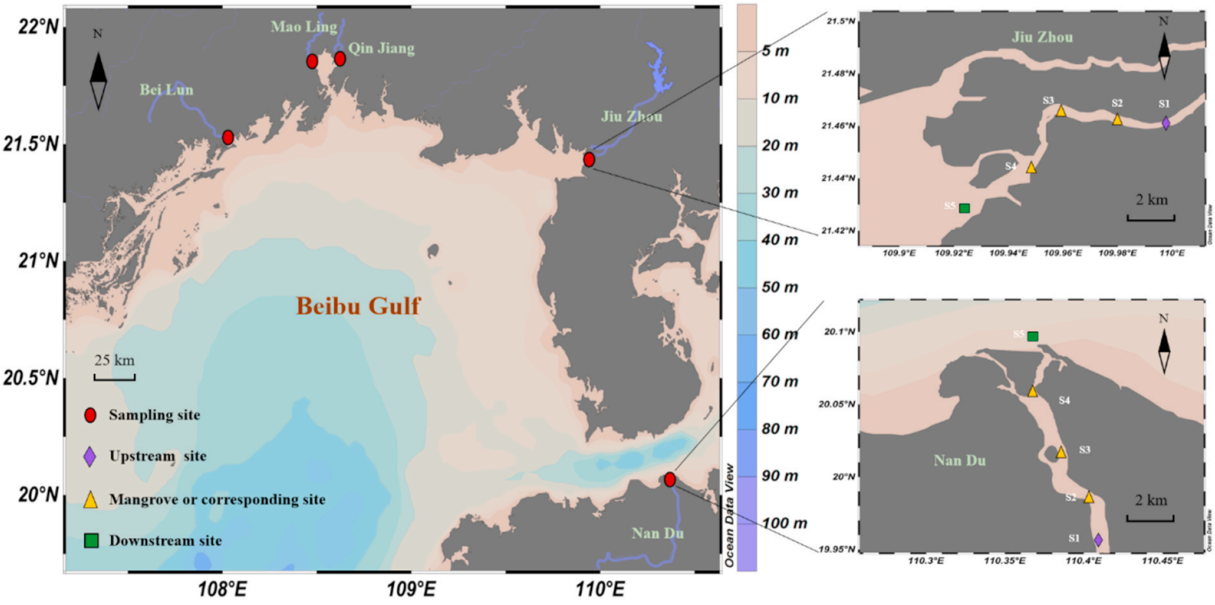

Fig. 1. Geographic location and sampling sites of ND and BL rivers. Other sampling sites of ML, QJ and JZ rivers were presented in Fig. S1.

2.2.2. *The isolation, quantification and identification of MPs in water and sediment samples*

For the water samples, the extraction of MPs was performed similar to the method reported by Hu et al. (2018). Briefly, the water samples were first subjected to a visual screening and the relatively large MPs were picked out and stored on filter membranes in glass Petri dishes. Then, the water samples were passed through 1.2 μm GF/C glass microfiber filter membranes (Whatman, UK) and the residues trapped on the membrane were rinsed into a 1000 mL beaker using hydrogen peroxide (30%). Finally, 200 mL of hydrogen peroxide (30%) was added to the beaker and the supernatant was passed through 1.2 μm filter membranes. The filter membranes retaining suspected MPs were placed in covered glass Petri dishes for analysis.

For the sediment samples, the extraction of MPs was performed similar to our previously reported methods (Li et al., 2019). Firstly, the collected sediment samples were wrapped in tin foil with an upward gap to remove moisture, and then placed in a drying oven (Yamato Scientific DX301, Japan) to dry to a constant weight at a temperature of 298.15 K for 48 h. Then, 200 g of the sediment was taken out and put into an Erlenmeyer flask while 10 mL of 30% hydrogen peroxide (H_2O_2) was added for digestion to remove soil organic matter (SOM). Hydrogen peroxide can be added repeatedly until the solution was clear in appearance. After that, 500 mL of potassium formate aqueous solution with a 1.5 g/cm^3 density was prepared and poured into Erlenmeyer flasks under constant stirring with a clean glass rod for thorough mixing. Eventually, the supernatant was filtered onto 1.2 μm filter membranes while the filter membrane was transferred to petri dishes.

The detection of suspected MPs on the filter membrane uses the stereoscopic microscope (Stemi 508, Germany) at 3–4 times magnification. Then these particles were examined using a micro-Raman spectrometer (Renishaw inVia, UK) (Fig. S2). Data were collected from a resolution of 100–9000 cm^{-1} with a laser excitation wavelength of 532 nm. The spectra were compared with a database from Renishaw Polymer database to verify the polymer types (Fig. S3).

2.2.3. *Quality assurances (QAs) and quality controls (QCs)*

The following QA and QC measures described in our previous studies (Jiao et al., 2021) were conducted in the present study. Firstly, the metal containers or samplers were used and latex gloves were worn to avoid sample contamination during the entire sampling process. Secondly, non-plastic products were used throughout the experiment and washed with Milli-Q water, while aluminum foil covered the open container and then put the container into the fume hood at the time of no experiment. Thirdly, the solvents used in the samples for sample processing and analysis (Milli-Q water, 30% H_2O_2, and potassium formate) were filtered through GF/C glass microfiber filter (Whatman, UK) prior to use. In addition, the results of laboratory analysis were adjusted through blank tests and no MPs were found in the blank samples.

2.3. *Characteristics of mangrove forests*

2.3.1. *Ecological indicators and hydrodynamic factors of mangrove forest*

All the ecological indicators, including the coverage area of mangrove forest, mangrove communities, alien invasive plant species, etc., in the Beibu Gulf were collected from other reports (Cao, 2010). River flow velocity within one month for each sampling site was continuously monitored twice (48 h each time). And the interval between the first and second monitoring was 15 days.

2.3.2. *Properties of sediment*

Total organic carbon (TOC) of sediments were measured by an Elemental Analyser (Elemntar in Germany, Variomacro cube) (Donato et al., 2011). Soil porosity was determined by an ASAP 2010 Brunauer-Emmett-Teller (BET)-N_2 Analyzer (Micromeritics, Norcross, GA). And, the total porosity was calculated from the dry bulk density and the measured grain density. The dry bulk density was calculated from dry weight and bulk volume given by the mercury porosimeter.

2.4. *Statistical analysis*

The abundance and characteristics of MPs collected from the water and sediment samples of the fiver river located and MWS on the Beibu Gulf were analyzed by the SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). All the diagrams were drawn by Origin 9.0 software (OriginLab, USA). Moreover, a linear regression and Pearson's coefficient were used to test whether there was a significant correlation between the interception rates and the external and internal factors, and $p < 0.05$ was considered to be statistically significant.

3. Results and discussions

3.1. *Interception of MPs from river to ocean by mangrove forest*

3.1.1. *Water*

MPs were detected in all sampling sites and their abundance varied from 18.0 ± 4.0 to 1695.0 ± 34.0 items/m^3 (Table S1). A typical MPs from surface water is presented in Figure S2. MPs abundances observed in this study were similar to our previous observation in the Mao Ling river estuary and the Qin Jiang river estuary (231.2 ± 70.0–1695.0 ± 34.0 items/m^3) of the Beibu Gulf (Li et al., 2019). Relatively high abundance of MPs has also been reported in Minjiang estuary (1245.8 ± 531.5 items/m^3), Jiaojiang estuary (955.6 ± 848.7 items/m^3), and Oujiang estuary (680.0 ± 284.6 items/m^3) (Zhao et al., 2015). Whereas, relatively lower abundance of MPs was detected in the Bei Lun river estuary (18.0 ± 4.0–102.0 ± 20.0 items/m^3) and Jiu Zhou river estuary (0.055×10^5–2.6×10^5 items/m^3).

As Fig. 2A displayed, the MPs abundances of all the other rivers displayed a significantly decreasing trend after flowing through the mangrove forest in the dry season ($p < 0.05$). While the decreasing trends almost disappeared once the river enter the estuary area without any presence of mangrove forest. Moreover, it should also be noted that the abundances of MPs in the downstream of JZ and BL river decreased to a relatively small extent (32 ± 1 items/m^3 and 25 ± 2 items/m^3), even lower than some reports about the MPs in deep sea or remote sites (Klein et al., 2015; Tan et al., 2020; Zhang et al., 2020). Spatially, the decline rates of MPs abundance from site S1 to S5 in the JZ river (185–32 items/m^3) and ML river (1225–220 items/m^3) with the presence of mangrove forest are one order of magnitude greater than that in the ND river (73–25 items/m^3) with the absence of mangrove forest. Similar results were obtained in the rainy season (Fig. S4).

From the viewpoint of the sources of MPs, it was an interesting but confused phenomenon for the below two reasons. Firstly, the upstream rivers were all surrounded by villages with low urbanization processes and population density, which produced relatively small fractions of plastic products. Secondly, many different sources existing downstream of rivers may accelerate the discharge of polymer litter, including the aquaculture, fishing industries, etc. At present, the strategies for control of microplastics pollution primarily focus on source reduction and the development of cost-effective clean up and remediation technologies (Ali et al., 2021; Rasheed et al., 2020b, 2021a, 2021b; Teixeira et al., 2021).

The only reasonable explanation was that there existed some MPs blocking processes or places in the middle of the river upstream and downstream. Combined with what we have discussed in the Introduction section, we speculated that mangrove forests blocked or perhaps trapped the transportation of MPs from the river to ocean.

3.1.2. *Sediment*

To validate our assumption described above, the abundance of MPs in the sediment collected from the river upstream, mangrove forest (or corresponding the sites for the ND river) and river downstream were separately detected, and the results were shown in Fig. 2B. Clearly, the

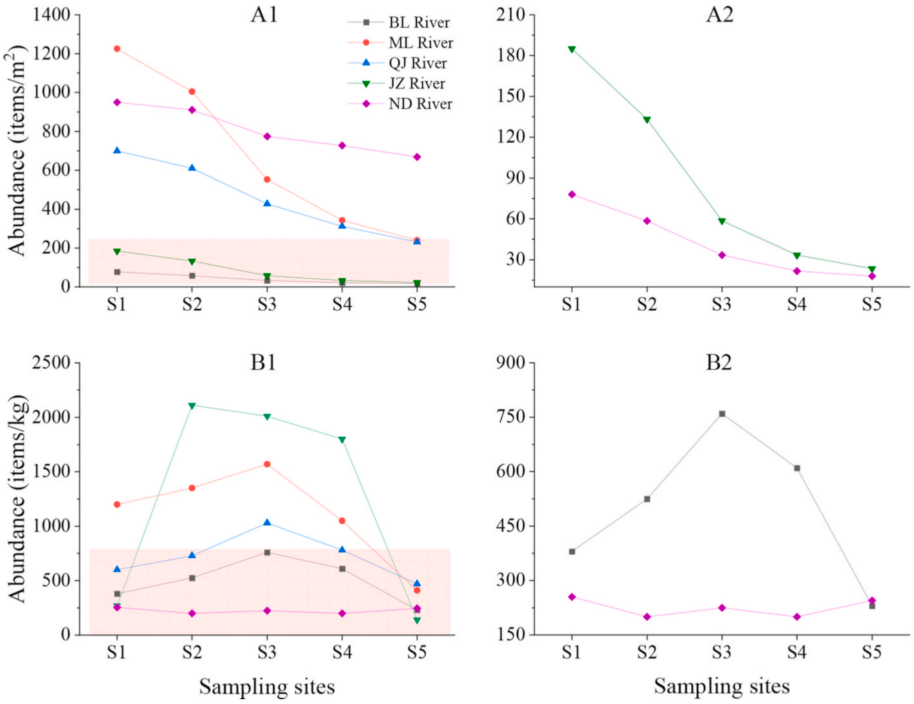

Fig. 2. The spatial distributions of MPs collected from water (A1 and A2) and sediment (B1 and B2) of the river at the dry season. A2 and B2 were the larger images of the two rivers with the smallest abundance (correspond to the red outline in the A1 and B1). S1 to S5 represents the sampling sites from the river upstream (S1), mangrove forest or corresponding sites (S2, S3 and S4) to river downstream (S5). ND river was the control group without the presences of mangrove forest. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

abundance of MPs in the upstream river sediments were almost the same as the downstream sediment (Table S2).

More importantly, except for the blank group (ND river), we can clearly conclude from Fig. 2B that the MPs abundance in mangrove sediment (S2, S3 and S4) were significantly higher than that of the upstream (S1) and downstream sites (S5, $p < 0.05$). The abundance of MPs in upstream/downstream sediments can be as low as 10% of that in mangrove sediments. Similar results were obtained in the rainy season (Fig. S4). Overall, once the rivers flow though the mangrove forest, the MPs in water were blocked, continuously deposited by nature and finally stored in the mangrove sediment or other matrix (plant, biota, etc.).

3.2. *The interception of MPs by mangrove forest*

For more convenient measurement and comparison, the interception capability of mangroves is quantified using the following formula: $C_I = (C_U - C_D)/C_U \times 100\%$. The C_I represents the interception rate, which indicates the interception ability of mangrove forests to MPs. C_U and C_D separately represent the abundance of MPs in water samples collected from the front zone and the corresponding back zone.

Obvious differences were obtained for the MPs interception rates of mangrove with and without mangrove forest (Fig. 3), indicating that mangroves forest is a strong obstacle during the migration of terrestrial MPs to the sea. Furthermore, the interception of MPs by mangrove forest was almost immune to their abundance. For example, the mangrove forest on the estuary of JZ river displayed the highest interception rates (mean: 39.25%) with abundances as little as 185 items/m^3 (S1) –32 items/m^3 (S5) in the dry season (Table S3).

In addition, for the mangrove forests studied, the interception rates of MPs in the dry season (December) were higher than that in the rainy season (August). In the rainy season, the significantly increased water flow rate of rivers makes easier for MPs to release from mangrove sediment, leaf litter, etc. (Corcoran et al., 2020; Kumar et al., 2021; Li et al., 2021), which may be the dominant reason for the above phenomenon. But this process was only effective on the deposited MPs in mangrove forest, and has almost no effects on the other “blocked” fractions. Another reason for the small drops of the interception of MPs was that the seawater may enter the river estuary and partially offset the influences of river floods.

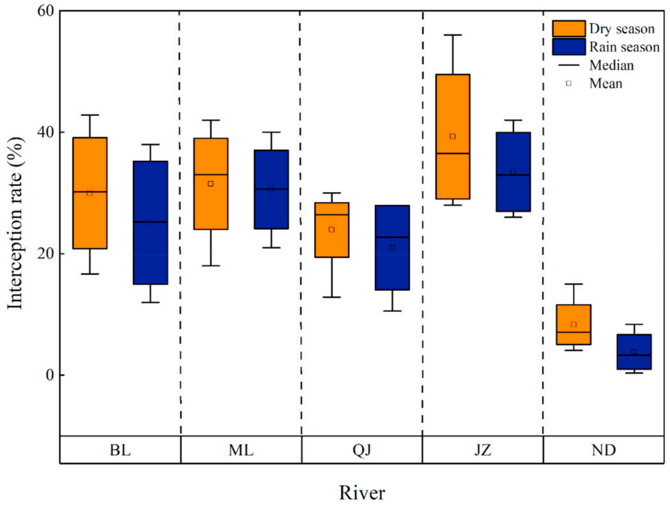

Fig. 3. The interception rates of MPs at difference zones of rivers of the dry season and rain season.

From Fig. 4, it can be clearly concluded that the characteristic of MPs may also affect their inception rates. For the type characteristic, the differences of interception rate of dominant type of MPs (PS, PE and PP) were obvious ($p < 0.05$). As shown in Fig. 4A, the mean and median interception rate for type ranked in the following order: PS > PE > PP, which might be attributed to the different types of MPs have different densities (PS (1.04–1.10 g/cm^3) > PE (0.89–0.98 g/cm^3) > PP (0.83–0.92 g/cm^3)). Generally, the MPs with higher density were more easily deposited onto the interface of water and sediment (Kim et al., 2021). For the size characteristic (Fig. 4B), the interception rates for MPs with relatively small size (<500 μm and 500 μm-1 mm) were lower than the larger size (>1 mm). Porosity of mangrove sediment is always considered as the major site for blocking external particulate matter (PM) from water or biota. Similar to their light fractions, one of the dominated reasons for the interception of MPs was the match-degree of

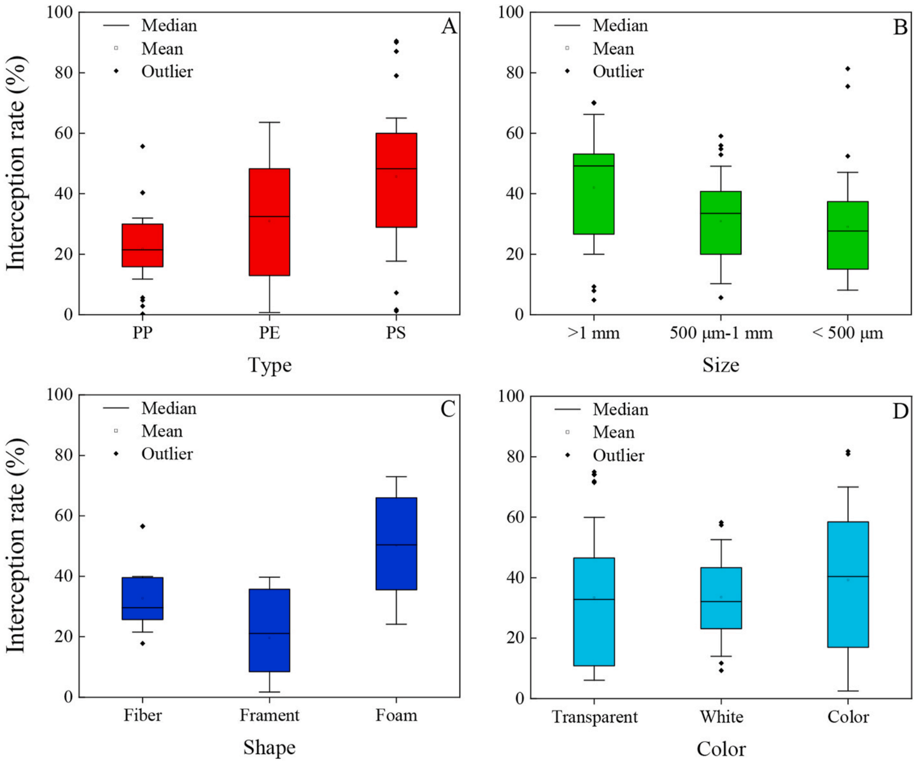

Fig. 4. The interception rates of different type (A), size (B), shape (C) and color (D) of MPs in water during dry season. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

porosity and MPs size. In other words, larger MPs were more easily to block mangrove sediment.

For the shape characteristic, as Fig. 4C displayed, the differences of MPs interception rates with different shapes were obvious, and the foam MPs displayed the highest values. The second one is the interception rate of fiber, ranging from 22.5% to 41.2%, and the last is the interception rate of fragment, generally lower, ranging from 0% to 40%. On one hand, compared with fragments and fibers, foams observed in experiments usually have larger sizes, while MPs with larger sizes are not easy to pass through the "interception net". On the other hand, as previously reports showed, the MPs with more regular shape are easier to settle because they have less settling resistance than MPs with irregular shapes (Kowalski et al., 2016). Furthermore, irregularity of the shape may lead to instability in the particle motion affecting rotating, oscillating or tumbling of the particle which decreases the sinking velocity markedly (Raju et al., 2020). This means that fragments with more regular shape have less settling resistance than fibers and thus settle into mangrove sediments more easily. For the color characteristic, no obvious differences were obtained for the interception rates colorful, transparent and white MPs. This means that the interception of mangroves may not be selective to different colors of MPs.

3.3. The dominant factors determined the interception of MPs by mangrove forest

Martin et al. demonstrated that the trapping of river plastic debris was largely due to the developed root system and high net primary productivity (Martin et al., 2019). And, the composition and structures of sediment, as our previously reports showed, also affect the spatial distributions of MPs in mangrove forests. Meanwhile, some other reports confirmed that the blocking of small particulate matter mainly depends on the hydrodynamic factors (tidal range, velocity, etc.) (Zhang et al., 2020b). In other words, there exists no clear conclusions about which factors played the dominant roles in the interception rates.

To explore the related mechanisms, the relationships between the interception rates of MPs by mangrove forest and their related factors, including the ecological indicators of mangrove forest, the properties of sediment and hydrodynamic factors, were explored, and the results were presented in Fig. 5.

3.3.1. Ecological indicators of mangrove forest

As an ecological indicator, the area of mangrove along the river is our first consideration. Unexpectedly, it has not been found to correlate with the average interception rate of the river (Fig. S7). The inconsistency of mangrove species may be responsible for this result (Srikanth et al., 2016). For example, the mangrove forest area at JZ is relatively small, but its main mangrove species is *Bruguiera gymnorrhiza*, with more developed morphological characteristics of root system, which may form more interception points for microplastic (Table. S4). Therefore, biomass, an ecological indicator that can directly measure the standing crop of plants, is our further consideration target.

As shown in Fig. 5A, expectedly, a significant correlation between the interception rate and total above biomass (TAB) of the corresponding mangrove was observed with the p values less than 0.01 and correlation coefficients (R^2) is 0.721, meaning the TAB is one of the factors that affect the interception rate of mangrove. In other words, the TAB of mangroves, rather than their corresponding areas, were the important factors affecting the interception of MPs.

However, to the QJ region in both the dry and rainy seasons, two outliers were observed in Fig. 5A, revealing that some other factors may also affected the interception rate of MPs. Invasive species in mangrove forests may be responsible for the impact on interception rates. There existed some arguments to support our conclusion. Firstly, a large number of invasive species were found in QJ, mainly *Spartina alterniflora* and *Sonneratia apetala*, which are perennial herbs and trees, respectively. They are salt tolerant plants and have strong competitive advantages in mangrove wetlands along the coast of China, which adversely affects the growth and development of mangrove seedlings

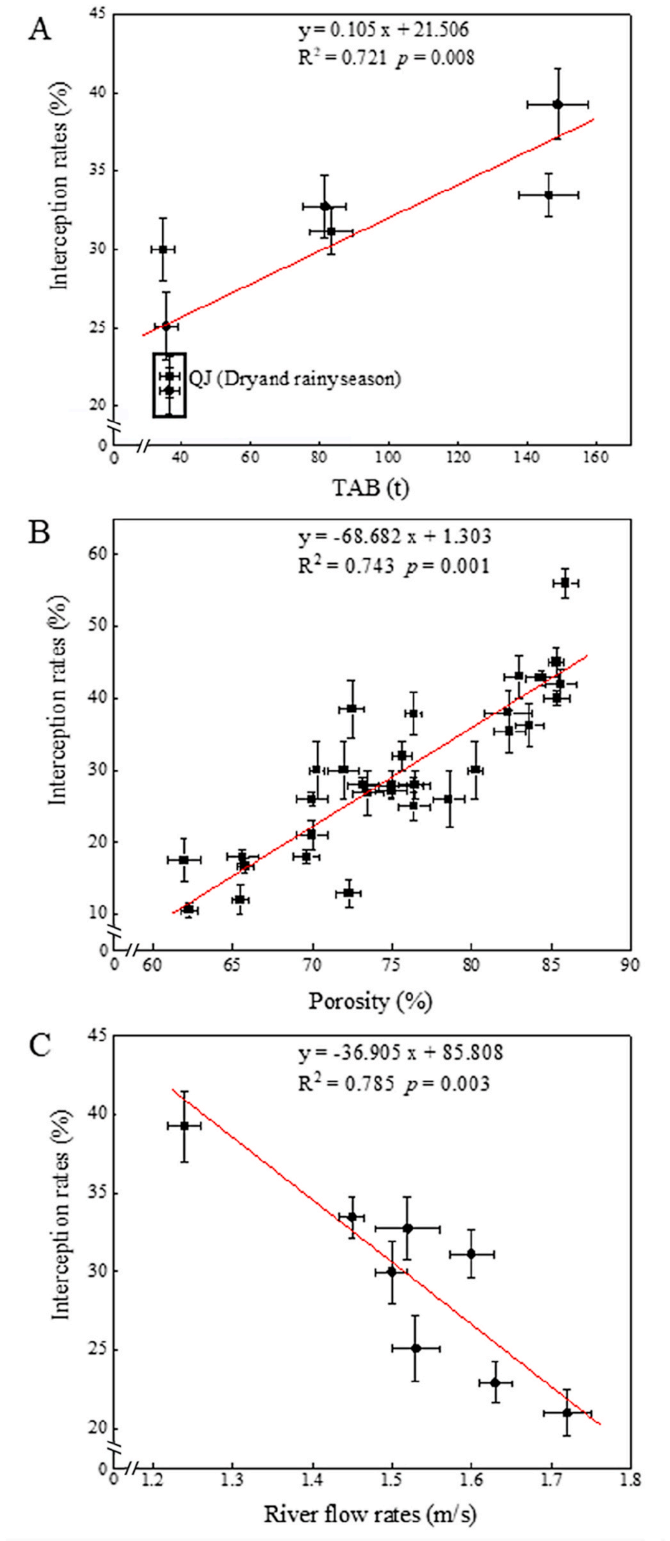

Fig. 5. The relationships between the interception rates of MPs and TAB (A)/ porosity of sediment (B)/river flow rates (C).

(Feng et al., 2017). Secondly, rapidly multiplying invasive species have crowded out mangrove growing areas, sharply decreasing their growth space and robbing them of the nutrients they need to grow (Biswas et al., 2007; Li et al., 2011).

Undoubtedly, after these anomalies were removed separately, the correlation between the TAB and interception rate of mangrove improved significantly, showing an extremely significant correlation (Fig. S8). The R^2 value range increased from 0.721 ($p = 0.008$) to 0.851 ($p = 0.003$). Overall, it can be concluded that the interception rates may depend on the mangrove community and their coverage area.

3.3.2. *Properties of sediment*

Except for the ecological indicators, the properties of sediment (organic matter content/function groups, porosity, etc.) may affect the spatial distribution of the MPs and their interception rates (Table. S5). Therefore, linear regression analysis was performed using the interception rate of each adjacent area of the mangrove forest and the SOM and porosity of the corresponding sediment, respectively.

However, different from our assumption, no correlations were observed between the sediment organic matter (SOM) content/function groups and the interception rates ($p > 0.05$) (Fig. S9). These divergent findings revealed that the SOM was not the dominant MPs adhering sites in mangrove sediment. Whereas, the pores of the sediment may better match or accommodate the MPs for the presence of linear relationships between the interception rates and porosity ($p < 0.01$, $R^2 = 0.743$, Fig. 5B). The two above results indicated that pores are more likely to “blocked” plastic debris than organic matter in mangrove sediments (Ola et al., 2018).

3.3.3. *Hydrodynamic factors*

Prior to evaluating the role of hydrodynamic factors in the interception of MPs, the average flow rates were firstly measured in the dry season with the values of 1.50 ± 0.02 m/s, 1.52 ± 0.04 m/s, 1.63 ± 0.02 m/s and 1.24 ± 0.02 m/s for BL, ML, QJ, and JZ rivers, respectively. Little higher flow rates values were obtained in the rainy season (Table S6). As shown in Fig. 5C, a significant negative correlation was found between the interception rate of MPs and the corresponding flow rate in mangrove forest ($p < 0.05$, $R^2 = 0.785$).

Previous reports have found that water flows into mangroves tend to form dense turbulence due to the luxuriant roots and stems of mangroves, leading to the formation of floccules of MPs and sticky suspended sediments (Zhang et al., 2017). However, unlike mangroves not adjacent to a river, mangroves along a river have less opportunity of floc settlement due to continuous scour of the river (Le Nguyen and Vo Luong, 2019). In short, currents with persistent and high velocities in the mangrove forest are expected to impede MPs and floc settlement (Wang et al., 2019), and these complexes are tending to deposit when water flow velocity reduces (Heeb et al., 2012).

4. Conclusions

Our results suggest that the mangrove forests played important intercepting roles in the transportation of MPs, with the interception rate of riverine MPs by mangrove forests ranging from 12.86% to 56% in the dry season and 10.57%–42% in the rainy season. Moreover, MPs with different characteristics (size, type, etc.) had quite a distinct interception rate from each other. Further, the interception ability of mangrove forest depended on the ecological indicators of mangrove forest, the properties of sediment and the hydrodynamic factors.

Findings of this work may help us improve our understanding of the MPs transporting from rivers to the ocean as well as the accuracy of the model for estimating the flux of MPs from land to the ocean. Globally, the interceptions of MPs by mangrove forest may be extremely large, even a small fraction of them eventually retained in this ecosystem, and they will still account for a large proportion of the ocean environment around the world. Besides, our study disclosed another important ecological function of mangrove forest (ie. interception of MPs). Quantification of mangrove forests intercepting MPs in rivers as a factor affecting MPs retention in global rivers can be a future research direction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.112939.

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